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Multi-spectral Shock-layer Radiance Flight Experiment Plan

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Abstract

The Dual-mode Experiment on Bow-shock Interactions (DEBI) project is designed to contribute further understanding toward the aerothermochemistry associated with hypersonic flight for interceptor applications within the Earth's atmosphere. Such detailed understanding is required to accurately model the optical radiation from high temperature flows. A main component of an interceptor target acquisition and tracking system suite is the optical sensor(s). Future missile interceptors are projected to fly at hypersonic velocities and will be expected to acquire and track the threat while traveling within the atmosphere. An interceptor traveling through the atmosphere at hypersonic Mach numbers will cause a bow shock and experience aerodynamic heat loading that increases temperatures on

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external surfaces; including optical windows. Further, thermal excitation of species occurs in the flow-field around the interceptor. Emissions from hot optics and/or excited constituents in the sensor's field of regard can lead to sensor blinding in some regions of the spectrum. It is necessary to acquire dual-mode (ultraviolet and infrared) data during the this flight experiment to improve and/or validate state-of-art models developed under Ballistic Missile Defense Organization's (BMDO) Innovative Science and Technology Program. This paper summarizes the flight experiment, the innovative solutions, and our "lessons learned" during the design and development of the DEBI instrumentation suite. Problems addressed were: (1) how to best detect and transport signals predicted in the short wave and mid wave infrared spectrum; (2) what detectors and wavelengths are best suited to optics constraints; (3) what new materials were necessary to improve signal to noise for a sensible acquisition system; and (4) how to design an optical payload that can perform as required in a harsh environment. Ultimately, the intention of this work is to provide BMD engineers and scientists the predictive capability necessary to design sensor systems that will be effective under flight conditions.

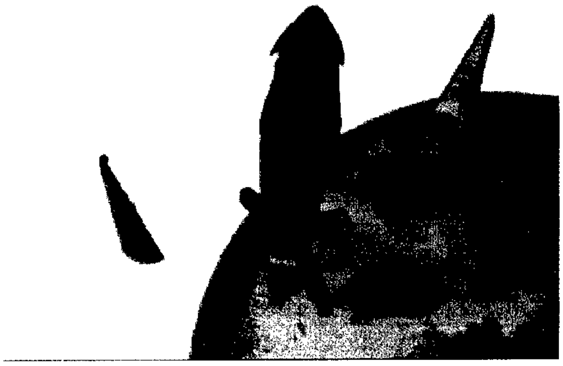


Figure 1. Illustration of in-flight hypervelocity induced bow-shock on nose of the DEBI experimental vehicle.

Introduction

Current and planned ground-based BMD systems rely on optical seekers with a hit-to-kill (HTK) strategy or blast fragmentation warhead to impact the incoming warhead. For this, the kinetic kill vehicle (KKV) must sense and track the target candidate and carry out the maneuvers required for the HTK intercept. For endo-atmospheric interceptors flying at hypersonic velocities the aerodynamic heating loads will significantly increase temperatures on external surfaces, including optical windows. Further, thermal excitation of species occurs in the flow field around the KKV. Given that the seekers operate in the infrared spectrum, emissions from hot optics and/or excited constituents in the sensor's field of

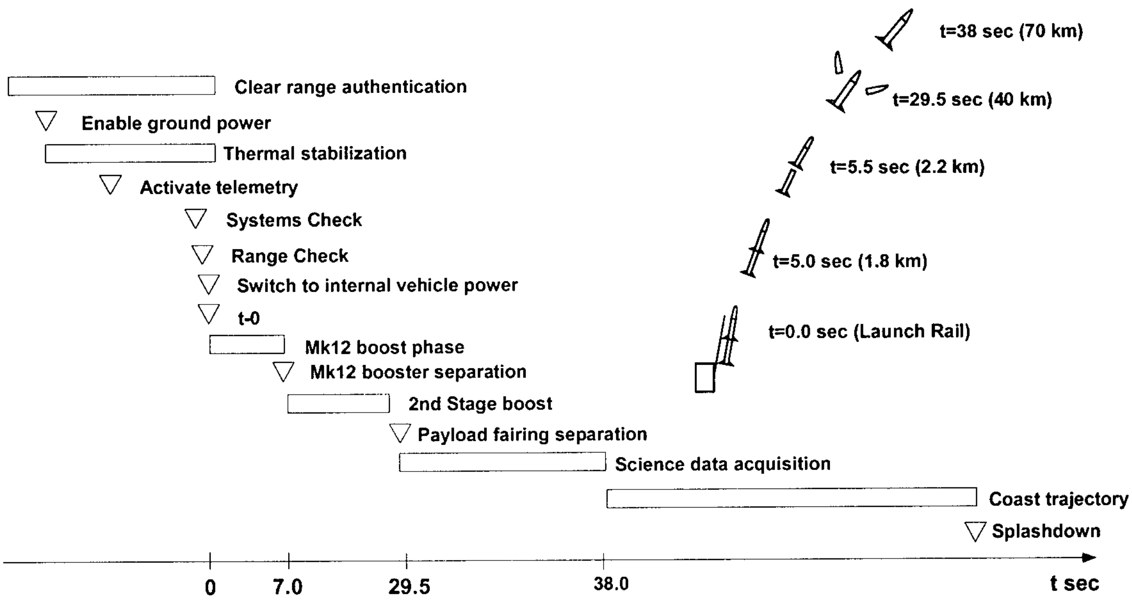


Figure 2. DEBI mission operations are concluded within first forty seconds of flight.

regard could lead to sensor blinding in some regions of the spectrum. The DEBI program is designed to further the understanding of chemistry associated with hypersonic flight in interceptor applications within the Earth's atmosphere. The DEBI measurements are carefully designed to examine atmospheric emissions in the shock-heated air and not aperture window emissions. Dual mode sensing (Ultraviolet and Infrared) will be employed and the data obtained in the flight test will be used to improve and/or validate state-of-art models developed under the Innovative Science and Technology program. Reference [2] describes the operational context for a two color MWIR/UV-Visible seeker. Ultimately, the program should provide BMDO the predictive capability necessary to design sensor systems that will be effective under real flight conditions.

Mission Operations

The DEBI experiment duration is estimated to be approximately forty seconds. The experiment delivery begins from the launch site at NASA's Wallops Island Flight facility (NASA/WFF). The experimental vehicle design reference requirement is to reach an upward velocity of 3.5 km/s at altitude of 40 km. In-flight data is to be acquired as the payload ascends and commences at 40 km following payload nose cone separation and continues through 70 km altitude. A Terrier-Malemute launch vehicle with MK-12 Terrier motor was determined to provide sufficient delta V to meet the experiment requirements on ascent. Figure 2 depicts the typical mission operations for the DEBI flight on the NASA/WFF range.

Science

As stated above, an overall goal of the IS&T program is to provide the predictive capability necessary for BMD scientists and engineers who are tasked to design and deploy effective sensor systems for target acquisition and tracking in future atmospheric interceptor systems. The major goal of the DEBI flight is to characterize the outboard optical environment associated with the flight of a hypersonic interceptor in the atmospheric phase of flight. Interceptor window and sensor environments have not been spectrally characterized at higher speeds in controlled, flight conditions. The DEBI flight provides this opportunity for far longer times than could be acquired in shock tubes and with realistic boundary conditions as found in free flight. DEBI is the third in a series of sounding rocket flights. The first two missions, Bow-shock I and Bow-shock II, focused on the Ultraviolet (UV) region of the spectrum and successfully provided data needed to improve predictive capabilities in UV wavelengths by four orders of magnitude. DEBI will focus on the Infrared (IR) region of the spectrum [2] and employ a suite of instruments to provide data on flow-field chemistry from the mid-to near-IR in the altitude range of interest (approximately 40 to 70 km) and at a representative nominal hypervelocity of 3.5 km/s. These data will then be used to refine the aerothermochemical models. UV instruments will also be used to obtain anchoring data for comparison with previous flights. The use of both UV and IR instruments also fulfills the secondary objective of demonstrating a dual mode system as a possible solution to potential sensor blinding issues. The flight will provide compelling evidence to demonstrate whether a UV seeker onboard a slender-shaped vehicle will experience any shock-layer interference or window heating problems. Unlike the IR, it is anticipated from pre-flight calculations that the window will remain

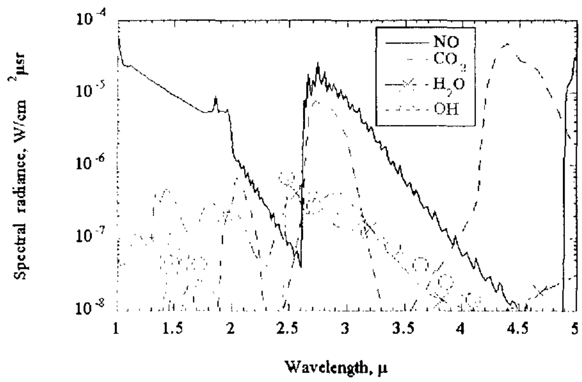


Figure 3. IS&T aerothermochemistry model predicted response intensities for measurable species at 40 km altitude from induced bow-shock excitation at 3.5km/s.

transmissive in the UV and the shocklayer radiance will be below the detectivity limits of a UV instrument. For the experiment, the forebody design will be similar to that currently used in BMDO's Atmospheric Interceptor Technology (AIT) program. The similarity assures the flight data is obtained with a relevant configuration. Figure 3 shows the pre-flight predicted intensities for molecular spectra excited by the bow-shock at

3.5 km/s speed and 40 km altitude. We expect the flight data to verify both the magnitudes and spectral features shown in Figure 3. Based on our experience with earlier flight experiments we expect there could be important differences in both predicted signal levels as well as radiating species. The species presently modeled are idealistic in that they represent IR emitting species formed by reactions of shock heated air (N_2, O_2, O, NO, NO_2, CO_2, H_2O, OH) only. Detectors covering a wide spectrum of measurements are described in the instrumentation section. Note that a few of the selected detectors correspond to peaks and valleys of the species shown in Figure 3. IR performance is expected to degrade during vehicle ascent to higher altitudes as aerodynamic heating occurs at the apertures. Full details about the predictions can be found in reference [3].

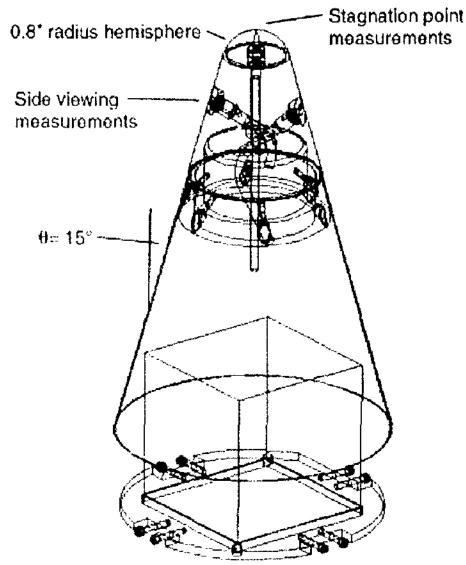


Figure 4. Fiber optics stagnation and side view conduits positioned in DEBI payload nose tip.

Instrumentation

The instruments were designed and are being fabricated as three separate instrument packages for the DEBI experimental flight. The instrument packages consists of detectors imbedded within a radiometer, a spectrometer, and two UV photometers. The detectors are interconnected to apertures via lens system and fiber optic bundles. The apertures are positioned at the vehicle stagnation point and two symmetrically aft-stationed points downstream of the vehicle nose. Data to be acquired are collected from 16 scanning spectrometer channels; 2 UV channels, 6 short wave infrared (SWIR) channels, 8 mid-wave infrared (MWIR) channels, and an array of temperature sensors. Two additional data channels in the IR radiometer are dedicated to determining the MWIR detector background and the payload system noise levels. The UV detectors provide legacy data to Bow-shock I and II (BSUV 1 and 2) experimental flights.

The payload nose tip for the DEBI vehicle is illustrated in Figure 4. This design was chosen to be representative of the Atmospheric Interceptor Technology (AIT) program so that data collected will be representative of interceptor flight. Each measurement location on the nose cone tip is fitted with a recessed sapphire lens connected to a fiber optic bundle. Table I summarizes the main characteristics of the flight scientific optical instrumentation. The table provides the onboard location and viewing information for each instrument as well as center wavelength and optical bandpass. Significant detector features and strategies as well as the intended radiating species are summarized.

DEBI UV fiber optics are well understood from previous flight experience. However, the IR fiber optic bundles provided a challenge to the design and fabrication of the DEBI payload. The primary technical problem was in selecting the appropriate fiber optics materials that met our link budgets and could also survive the environments induced from the flight and detector thermal requirements. Previous ultraviolet experience did not have an efficient carry-over into the infrared portions of the spectrum. DEBI planned for two severe environmental factors. The first environmental threat is thermal cycling during ground segment integration and checkout. During chill-down cycles there is high likelihood for direct liquid nitrogen (LN_2) coolant contact with some instrumentation components and the fiber bundles. The other environmental concern was the acoustic-vibration flight environment. We selected fluoride glass fibers to meet all our IR requirements and used UV grade quartz fibers for the UV data channels. There was a trade off in the selection of the fluoride glass fiber material. The fluoride glass fibers were more brittle than the fiber optic materials used in Bow-shock I and Bow-shock II. Consequently, the fluoride fiber material did not

have a tight bend radius, which in turn created major design constraints with regard to the positions and orientations of the instrument packages. Figure 5 shows a computer aided

Table 1. Summary of onboard science instrumentation.

Meas. #	Fiber Location at Aperture	Instrument	Spectral Range	Comments
1	Stagnation point	UV photo-multiplier	0.24μ center wavelength 0.043μ bandpass	CsTe photo-cathode photo-multiplier detectors operated in photon counting mode
2	Side station	UV photo-multiplier	0.24μ center wavelength 0.043μ bandpass	CsTe photo-cathode photo-multiplier detectors operated in photon counting mode
3 – 8	Side station	MWIR	3.0 - 4.0μ wavelength with ~0.2μ spacing and ~0.2μ filter bandpass specifically: 3.07μ CWL 0.19μ BP 3.21 0.2 3.43 0.19 3.64 0.17 3.80 0.18 3.93 0.16	Micro Optic Multispectral Radiometer
9	Side station	MWIR	3.45μ center wavelength with 0.54μ filter bandpass	Micro Optic Multispectral Radiometer
10	Side station	MWIR	4.34μ center wavelength with 0.2μ filter bandpass	Micro Optic Multispectral Radiometer tuned for CO_2
11	Side station	SWIR	0.98 μ wavelength 0.23μ bandwidth	Micro Optic Multispectral Radiometer
12	Side station	SWIR	1.27 μ wavelength 0.3μ bandwidth	Micro Optic Multispectral Radiometer tuned for O_2
13	Side station	SWIR	1.54 μ wavelength 0.35μ bandwidth	Micro Optic Multispectral Radiometer tuned for OH
14	Side station	SWIR	1.9 μ wavelength 0.4μ bandwidth	Micro Optic Multispectral Radiometer tuned for CO_2
15	Side station	SWIR	2.3 μ wavelength 0.064μ bandwidth	Micro Optic Multispectral Radiometer tuned for predicted window
16	Side station	SWIR	2.7 μ wavelength 0.25μ bandwidth	Micro Optic Multispectral Radiometer tuned for CO_2 and NO
17-24	Stagnation point	Scanning IR spectrometer	1.0 - 3.0μ wavelength	500Å bandpass
25-32	Side station	Scanning IR spectrometer	1.0 - 3.0μ wavelength	500Å bandpass
33-N	N/A	Temperature	N/A	Resistive temperature elements

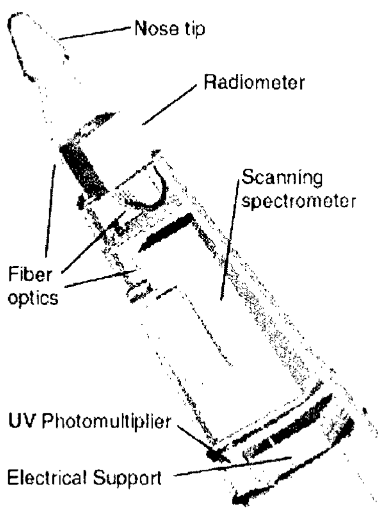


Figure 5. Rendering of CAD model showing fibers connecting the stagnation point and side looking directions from nose tip to appropriate instruments using long radii bends.

design model showing the fiber optic connections between the stagnation and side looking apertures and the appropriate detectors within the radiometer, spectrometer, and UV detectors. Notice that in Figure 5 the radiometer is positioned two decks above the spectrometer. This resulting radiometer position was primarily to accommodate having acceptable bending radii. We benefited from the ability to satisfy optical fiber long radius constraints and improve vehicle stability by moving the center of gravity forward. To reduce the risk of IR fiber optic breakage during flight or during handling, pre-bends were designed and fabricated into the fiber bundle harnesses. Handling is being kept to a minimum.

The UV detectors provide legacy data because they overlap with the Bow-Shock I and Bow-Shock II experimental flights. One special feature of the DEBI UV instruments is that they are designed to measure very low intensities in side-viewing direction.

The MWIR and SWIR radiometers have InGaAs and HgCdTe photodiode detectors coupled to windows with IR fluoride glass fibers. The scanning IR spectrometer has a fast f/0.5 relay lens system at the exit slit and a stepper motor driven diffraction grating with InGaAs photodiode detectors for short wavelength regions, extended InGaAs photodiode detectors for the intermediate wavelength regions, and photo-voltaic short wavelength HgCdTe detectors for the longest wavelength regions. When our team received the detectors they were configured differently than what was expected. Procurement was not an option because of long lead times associated with the small quantity used in the DEBI experiment. This made necessary a modification to focus the appropriate amount of energy upon the detectors as received. We engineered a system of lenses to solve this problem. One key element used to get an acceptable signal to noise ratio for the MWIR was the implementation of chalcogenide glass for a lens material. The chalcogenide material has a high index of refraction (~2.5), was readily available, and easily machined by skilled lens makers. Consequently the chalcogenide glass material made it possible to get an appreciable amount of light upon the MWIR detectors to meet acceptable expected signal to noise ratios (SNR) for the detector material. All detectors will be cooled below 193K before flight and provided with sufficient thermal inertia to maintain acceptable temperature limits for the in-flight 40 second duration.

Payload

Payload elements include structures, thermal control, power, telemetry, command and data handling, and the payload fairing. The payload subsystem is built with the requirement instruments survive the stressful flight experience sufficiently long to satisfy the science objectives to collect data over as large an altitude range as possible. The integration of instruments into a payload must provide a cold environment for the IR instruments, fiber optics and nose tip and an even colder environment for the detectors themselves while providing a warm environment for all the rest of the payload electronics. It must protect this internal environment from the extremely severe aeroheating in the dense atmosphere to point at 40 km when the rocket motor burns to completion and the velocity is 3.5 km/s. At this time we require a chemically clean and cold measurement surface of desired shape to be presented to the flow field. The measurement nose tip is designed to prevent black body radiation from the tip itself from entering the fiber optics until the payload reaches an altitude of approximately 70 km. An entire section of the

payload including the nose tip will be isolated from the rest of the payload and the outside environment and kept at a temperature of approximately –60° C. An ejection clamshell styled nose cone will provide protection for the cold section from the extreme ascent aeroheating.

The measurement surface will be quickly heated after the nose is ejected. It should be noted that copper is used for the forward hemispherical surface to absorb the strong heat flux without getting so hot its black body radiation will mask the atmospheric radiation to be measured. Another key to preventing this interference is to use a cold sapphire lens to image the end of the fiber bundle to a location outside of the nose tip. The fiber bundle and lens are recessed within the nose tip and will be slow to heat. The aperture that they view through is kept outside of the optical field of view. At least one scatter is required for black body radiation to enter the measurement system.

Ejection Nose Cone

The ejection nose cone design is very critical to the success of the DEBI program. There are several difficult requirements that must be met that are entirely unique to DEBI that did not exist on

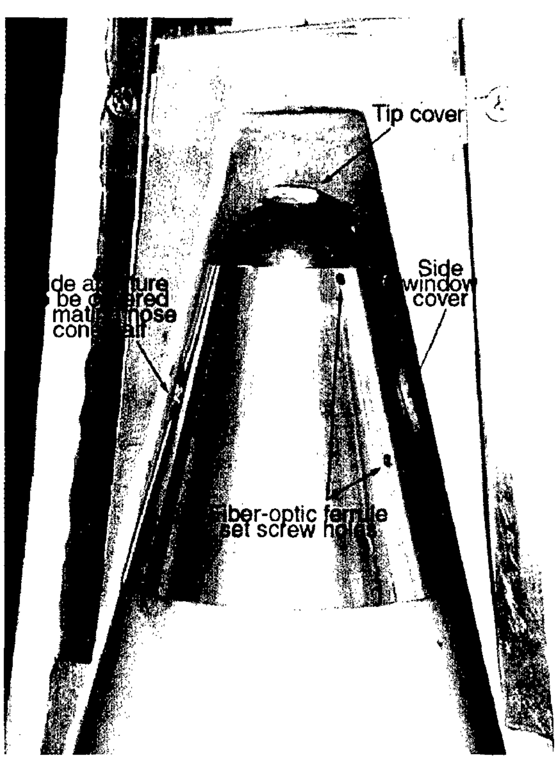


Figure 6. DEBI nose tip showing half of the ejection cover and aperture covers.

the related Bow-shock I (BSUV I) program. They are as follows:

1. Meet the demanding thermal constraints of allowing the coldest part of the payload to remain cold and still be within inches of the nose cone ejection electronics that must remain warm. The thermal separation must be done without compromising the ability to separate the nose cone halves and without vacuum jackets and MLI to provide insulation.
2. Maintain a dry environment so that frost does not form on optical surfaces prior to launch.
3. Maintain protection from optical system frosting during the early stages of flight when the dynamic pressure on the outside of the nose cone is greater than the ambient pressure inside the nose cone at the optics apertures. During these conditions, the direction of flow of warm moist Virginia night air will be inward toward the very cold nose tip optics.

In order to meet the thermal requirements, the cold inner nose cone is separated from the outer stainless steel skin by a fiberglass inner shell. The photograph in Figure 6 shows the inner nose cone tip fitted within half the nose cone shell. The shell is built in two halves mounted to the stainless steel skin. The gap between the fiberglass shield and the stainless skin is filled with fiberglass building insulation. This relatively low-tech material was chosen because there are no significant trapped air spaces to retain moisture like are present within foams. It will be a material that is less difficult to purge than other options even though there are better insulators.

The separation v-joint at the base of the cone is mated to a steel ring at the top of the carbon fiber skin. Since it is in the cold section, it will be at or near the –60°C temperature. The section of the ejection nose cone forward of the fiberglass shell needs to be near ambient temperature for the proper operation of the ejection electronics. This is accomplished through thermal conduction from the surrounding air outside of the nose cone, warming the cone and its contents. The aft section of the ejection nose cone which can and will be cold is covered by an external foam insulator, which will be torn away upon liftoff. An approximate 80°C temperature differential will

Figure 7. Polyurethane coated nose section and payload skins stacked next to structure and housekeeping components.

need to be maintained across the aft 15 inches or so of the stainless steel cone without producing a lot of frost or ice forward of the insulation. The external foam insulator seemed to work satisfactorily during early testing without the ablative since the stainless steel nose tip material is a poor thermal conductor.

In order to minimize the infiltration of hot air into the ejection nose cone during flight, we have gone to considerable care to make certain that the nose cone halves fit together very well. In quantitative terms, that means that there should be no gap wider than 0.005 inches. A narrow gap is good from the standpoint of moist air infiltration into the nose cone during flight, but is just as bad with respect to purging of moisture trapped inside prior to flight. There are some tradeoffs that will have to be examined during integration testing to be certain that the purge is sufficient without making the cone excessively leaky during flight.

The tight fit between cone halves was obtained by placing one of the cone halves on a flat surface covered with a release film to which epoxy does not bond. An epoxy-quartz microsphere mixture was applied to the edges of the cone and the cone was then placed on the flat release film. When cured, this makes a precision flat surface. The cone half was removed from the release film and a layer of release film was applied to the new flat surface. Epoxy-microsphere mixture was applied to the other nose cone half and the two were bolted together. This produces an exactly mating surface between the two halves. After the two halves have cured, the assembled nose cone is coated with the ablative material to protect against the extreme aerodynamic heating upon ascent. After the ablative has cured, the two halves can be separated and the ablative trimmed. Since the glass-epoxy mixture used to achieve the precision joint cannot stand high temperatures, it relies on the ablative for protection during flight. An access door for pyrotechnic installation, the electrical umbilical and purge gas umbilical provided additional ablative application complications but seem to have worked out quite well.

The ablative is a polyurethane material that was selected because of its low activation temperature. When it has cured, it is quite soft, yet cuts and sands freely. When it bends it takes a moderate amount of force to make the bend but when the force is released it relaxes slowly. It should be an outstanding vibration dampening material unless its properties change dramatically with temperature. When subjected to heat from a welding torch, the ablative surface melts and evaporates keeping the inner surface below the activation temperature.

Figure 6 also shows graphite spring-loaded covers over each aperture prior to nose tip ejection. These covers are required to prevent frost from forming upon the cold optical surfaces. Each cover has a sapphire window to allow instrument testing prior to the beginning of the in-flight measurement period. A grain of wheat incandescent light bulb is included in the fiberglass inner shell and powered through the nose cone umbilical to provide a means of testing the instrumentation prior to flight.

The split line in the nose cone was intentionally indexed to the payload body so that it does not line up with either of the side view apertures. However, the forward viewing instrument will look directly into the split between the two fiberglass shells. It will certainly see black body radiation of unpredictable magnitude that will likely be different in flight than with either no outside lighting on the payload or with

the possibility of light-leaked outside illumination. We will choose the most beneficial cover/window option during payload integration and testing.

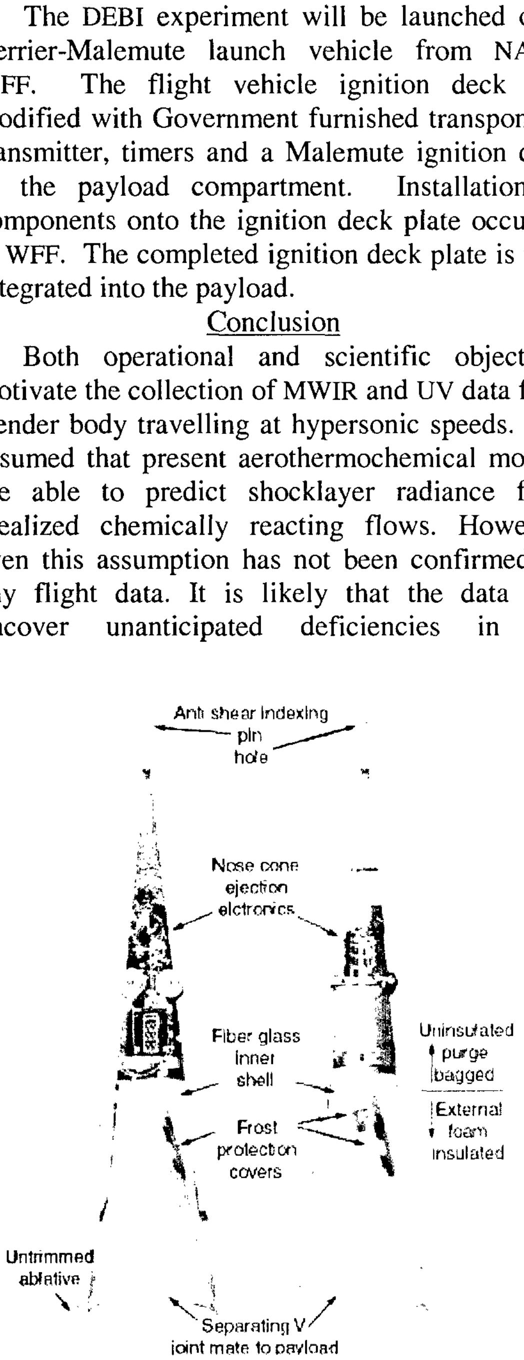
Figure 7 shows the entire stack next to the external appearance of the skin and nose tip section. Figure 8 shows the entire view of the split nose fairing to be jettisoned in flight. Figure 9 identifies the major sections of the payload.

Delivery Vehicle

The DEBI experiment will be launched on a Terrier-Malemute launch vehicle from NASA/ WFF. The flight vehicle ignition deck was modified with Government furnished transponder, transmitter, timers and a Malemute ignition deck in the payload compartment. Installation of components onto the ignition deck plate occurred at WFF. The completed ignition deck plate is now integrated into the payload.

Conclusion

Both operational and scientific objectives motivate the collection of MWIR and UV data for a slender body travelling at hypersonic speeds. It is assumed that present aerothermochemical models are able to predict shocklayer radiance from idealized chemically reacting flows. However, even this assumption has not been confirmed by any flight data. It is likely that the data will uncover unanticipated deficiencies in the aerothemochemical models. Spectra are crucial to validating radiance models. Several issues of concern for capturing in-flight data in the MWIR and SWIR portions of the spectrum data have been identified for those who plan to implement operational missions or experiments within this regime. We implemented solutions through design and materials selection for many of the issues identified. In addition to the scientific data, an important outcome of this flight will be the validation of our engineering solutions for small, affordable rocket flight experiments.



Acknowledgements

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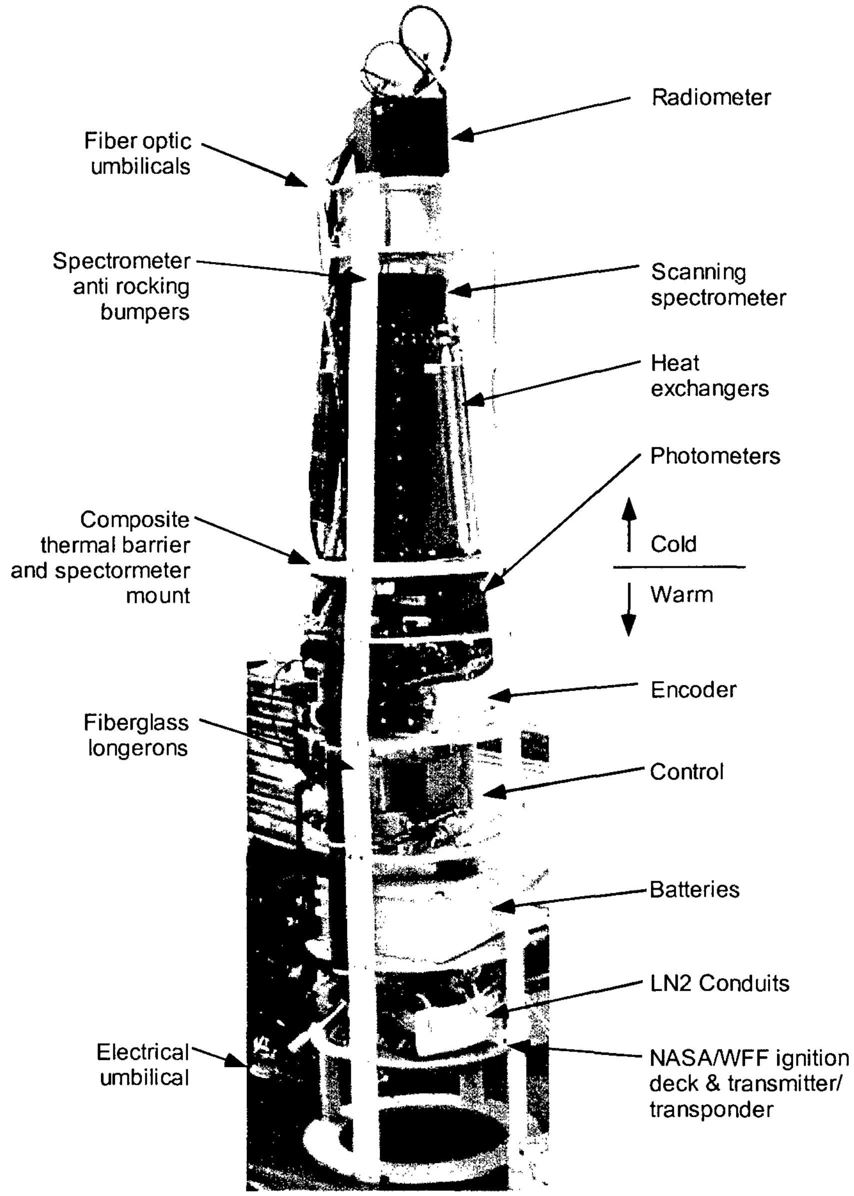

Figure 9. Payload structure, house keeping and communication, command, and control components.